# Critical issues for high-brightness heavy-ion beams – prioritized

1/19/07

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**SUMMARY**

This study group was initiated to consider whether there were any "show-stopper" issues with accelerators for heavy-ion warm-dense matter (WDM) and heavy-ion inertial fusion energy (HIF), and to prioritize them. Showstopper issues appear to be categorized as limits to beam current; that is, the beam is expected to be well-behaved below the current limit, and significantly degraded in current or emittance if the current limit is exceeded at some region of an accelerator. We identified 14 issues: 1- 6 could be addressed in the near term, 7-10 may provide attractive solutions to performance and cost issues, 11-12 address multibeam effects that cannot be more than partially studied in near-term facilities, and 13-14 address new issues that are present in some novel driver concepts. Comparing the issues with the new experimental, simulation, and theoretical tools that we have developed, it is apparent that our new capabilities provide an opportunity to re-examine and significantly increase our understanding of the number one issue – halo growth and mitigation.

## INTRODUCTION

The major emphasis of work in the Heavy-Ion Fusion Science Virtual National Laboratory (HIFS-VNL) is to address the top-level scientific question: "How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion?" Exploration of neutralized focusing and neutralized drift compression has enabled orders of magnitude increase in beam intensity; addressing the issue of how do we make our "hammer" more intense or effective. This report addresses the complementary issue of how large can we make our "hammer."

This study group was initiated to consider whether there were any "show-stopper" issues with accelerators for heavy-ion warm-dense matter (WDM) and heavy-ion inertial fusion energy (HIF), and to prioritize them. This need is pressing, because we are currently working on WDM accelerators, for which we need maximum performance. In addition, success in the upcoming ignition experiments in the National Ignition Facility (NIF) will provide motivation to aggressively pursue inertial fusion drivers, such as heavy-ion fusion accelerators and lasers – we need to be prepared.

We considered issues of near-term importance to warm-dense matter (WDM) as well as those relevant to the longer-term heavy-ion fusion (HIF) program. We emphasized issues that were likely to impact near term experiments, and that were amenable to testing in existing or near term facilities. Showstopper issues appear to be categorized as limits to beam current; that is, the beam is expected to be reasonably well-behaved below the current limit, and significantly degraded in current or emittance if the current limit is exceeded at some region of an accelerator. In one sense, these are soft limits in that an accelerator design will work at some level, however, if that level is too low, HIF will not be economically competitive. As with lasers, and high-energy physics (HEP) accelerators, investment in understanding and mitigating limits is necessary; it has been essential in obtaining funding for the NIF, the Large Hadron Collider (LHC) at CERN, and in the future, the International Linear Collider (ILC), which is currently in design and would benefit from additional cost cutting development.

We have made significant progress in measuring, simulating, and understanding electron and gas cloud effects and other high-brightness beam transport issues.

1. Made the first quantitative measurements of electron cloud (e-cloud) densities [1].
2. Measured and modeled the scaling of electron emission with the electronic component of ion energy loss in matter [2].
3. Measured and modeled the scaling of gas desorption with the electronic component of ion energy loss in matter [3,4].
4. Demonstrated the effectiveness of clearing electrodes for removing electrons [5].
5. Observed and simulated an oscillation involving bunching of electrons in a quadrupole magnet. Obtained good agreement on the frequency, wavelength, and amplitude of the oscillations [6].
6. Transported a 1 MeV, 0.18 A K+ beam through 10 electrostatic quadrupoles with little or no beam loss or degradation, even for the beam filling 60% and 80% of the electrode radius [7].

Many of these progress areas are "cross-cutting;" that is, they are of interest to HEP, nuclear physics, and other areas such as the Spallation Neutron Source (SNS). Our work has been well received by these communities.

Our major simulation code is based on a merge of the Heavy Ion Fusion accelerator particle-in-cell (PIC) code WARP [8] and the high-energy physics electron-cloud code POSINST [9], supplemented by additional modules for gas generation and ionization [10] as well as ion-induced electron emission from the Tech-X package TxPhysics [11]. The package allows for multi-dimensional (2-D or 3-D) modeling of a beam in an accelerator lattice and its interaction with electron clouds generated from photon-induced, ion-induced or electron-induced emission at walls, or from ionization of background and desorbed gas. The generation and transport of all species (beam particles, ions, electrons, and gas molecules) is performed in a self-consistent manner (the electron, ion and gas distributions can also be prescribed -if needed- for special study or convenience). The code runs in parallel and benefits from adaptive mesh refinement [12], particle timestep sub-cycling [13], a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps [14,15], and for relativistic beams, the recent discovery of a preferred frame of reference that reduces computation time by a factor of $2\gamma$ [$\gamma = (1-v^2/c^2)^{-0.5}$]. These advanced numerical techniques allow for significant speed-up in computing time (orders of magnitude) relative to brute-force integration techniques, allowing for self-consistent simulations of electron-cloud effects and beam dynamics, which were out of reach with previously available tools.

Comparing the issues with the new experimental, simulation, and theoretical tools that we have developed, it is apparent that our new capabilities provide an opportunity to re-examine and significantly increase our understanding of the number one issue – halo growth and mitigation.

We are now poised to apply the tools and understanding that we have developed to the following areas where improved understanding is needed. We expect that as longer accelerators are built, that we will need to reevaluate each of these questions, searching for more subtle effects. Answers to these questions will enable new generation accelerators to be built with assurance of operation that is not limited by electron or gas clouds, but ideally will also include the flexibility to find limits for each generation that will refine simulations for designing the subsequent generation.

The following questions should be evaluated separately for each type of source of electrons: beam tube emission (fills entire beam tube), end wall emission (maps out electron drift surfaces in quadrupole magnets), and gas ionization (maps out the overlap of gas and beam profiles). Because the cross sectional profiles of the electrons vary relative to that of the beam, the forces between electrons and the beam also vary; so the thresholds and effects are expected to vary for each type of source [16,17].

1. Are there beam threshold parameters below which e-clouds have negligible effects for each type of source?
2. How fast do increasing e-clouds degrade the beam for each type of source?
3. How large an e-cloud density can we tolerate from each type of source?
4. What is the maximum fill factor (ratio of beam radius to beam-tube radius) for minimal beam loss and degradation?
5. How much can we increase beam parameters with clearing electrodes to remove electrons, or other mitigation mechanisms?

Our accomplishments have resulted in a significantly better-understood scientific basis of heavy-ion drivers for IFE, than even five years ago. Progress on the remaining science issues listed above will enable driver level accelerators to be built with high confidence and improved performance. Several unique features of heavy-ion accelerators and conceptual power plants motivate this work:

1. Modularity or separability of the driver, chamber, and target factory is shared with other IFE concepts. Lasers also have a natural modularity of their drivers, some heavy-ion accelerator concepts share this also, which enables a less expensive development path.
2. A liquid-walled chamber that is not subject to radiation damage (multiple displacements of each atom does not change a liquid, but damages a solid), and is also low activation – which has been a long-term hope for fusion energy. HIF is compatible with liquid walls that are thick to neutrons; it is not currently clear that magnetic fusion energy (MFE) devices or laser IFE can be compatible.
3. Accelerators have demonstrated long lifetimes of many decades, and can be operated at 10 Hz or higher pulse rates.

4. The final focus optics can be electromagnets, with the windings shielded from neutrons sufficiently for 30 year lifetimes, and no damage to optical "surfaces" from radiation or debris resulting from fusion reactions.

Nevertheless, to compete with nuclear fission, heavy-ion accelerators and power plant concepts need innovation to reduce costs, and to obtain the maximum possible performance from each element of the concept. Maximizing accelerator performance forms the subject of this report.

## ISSUES

The number one issue was selected because it has a strong influence on other issues, is itself not well understood, and may be amenable to mitigation by relatively simple equipment.

**1. Issue: Halo formation** is still not well understood or experimentally validated [18-22]. Most of the beam current is within the beam "envelope", but a small fraction of beam ions undergo radial excursions of up to a few envelope radii; these are known as halo ions, and are the most likely to be lost by scraping off on the beam tube. Halo can be large immediately after the injector. It is important in all accelerators, but especially in high-fill factor WDM/HIF. [Fill factor is defined as the ratio of the beam major radius to the beam tube radius. Higher fill factor implies more halo scraping.]

a. **Methods:** Beam scrapers installed at positively biased electrodes in HCX will scrape the halo at up to 5 axial locations between 10 electrostatic quadrupoles. There are disk-shaped end electrodes from which electrostatic quadrupoles (ESQs) are cantilevered. Circular holes in the disks serve as beam apertures; the scrapers will reduce the apertures. The results will be diagnosed by Faraday cup, clearing electrodes, flush electrodes, and optical slit scanner measurements.
b. **Effectiveness:** Does this eliminate beam scraping in quadrupole magnets? Can we reduce initial halo sufficiently to study sensitivity to match. (Beam mismatch has been identified as a major source of beam halo [19].) Can we align scrapers sufficiently accurately relative to beam?
c. **Benchmarking:** Does this enable downstream simulations to better reproduce experiments, and reduce the need for an accurately reconstructed beam near the injector? Can we obtain predictive capability with simulations.

We propose experimental tests to determine the feasibility of halo mitigation by scraping, preferably using HCX: 180 mA, 1 MeV (Driver range). Fixed scrapers can be relatively simple, several sizes of apertures on a wheel or slider that could be inserted into beam path and changed while under vacuum would be better. Scrapers will be installed at positively biased electrodes (positive bias will suppress electron emission from the scrapers) at up to five locations in the 10-ESQ tank. (This is ~0.14 of a depressed betatron period for a core ion, but can be a larger fraction of a depressed betatron period for some halo ions.) A longer length of scraping could be achieved by also scraping in the matching ESQ region, where the beam cross sectional area decreases by a factor of 20.

Choosing the locations will involve considerations similar to those for the DARHT Beam Cleanup Zone (BCUZ) [23], where three solenoids focused the beam to a smaller radius, scrapers under two of the solenoids removed particles at large radii resulting in a low-longitudinal emittance and a more-square pulse. It is somewhat analogous to a laser spatial filter, which suggests that we focus the beam to a small spot, and scrape there with a single small aperture. [But with a space-charge dominated beam, scraping at multiple points along a betatron period should be effective with less degradation of the beam; unless we could locally neutralize the beam near a small aperture?] Aperturing over a 2 m length of 10 ESQs should provide halo-free operation for a comparable distance in magnetic quads, if the long drift plus the change in lattice period in the magnetic quads does not regenerate significant halo [24].

Halo ions will impact apertures near normal incidence. Measurements of electron emission and gas desorption show that emission scales as 1/cos, which decreases by factors ~20 from grazing to normal incidence, whereas desorption scales as a fractional power of 1/cos, decreasing by factors ~2-3 over the same range of angles [25,26]. Both electron emission and gas desorption are minimized for impact near 0°, i.e., normal incidence. Gas will cause charge exchange ($K^+ \rightarrow K^0$) and ionization ($K^+ \rightarrow K^{++}$ or higher ionization states), ions that change charge will hit the beam tube in a long accelerator.

We plan to use simulations to design and predict the feasibility of halo mitigation. Simulations of the injector through the matching and 10-ESQs will look for expansion of beam components, such as mushroom head seen in Grote's simulations [27], which provides a logical location to scrape the head. A major issue for these simulations is lack of an accurate reconstructed beam model at the injector, without which it may be difficult to determine the most effective locations for scrapers. We may be able to obtain such a reconstruction by splicing together conventional slit scans across the beam core with higher gain slit scans across the beam edges; thereby using existing instrumentation to increase the sensitivity of measurements in the halo region.

Analogous experiments and simulations to study minimization and control of halos with solenoid transport are desirable for comparison with quadrupole transport.

**Decision point:** Did halo scraping and beam reconstruction succeed? Success is defined as reducing clearing electrode currents to much less than the present minimum of 2-3 mA per electrode, with ionization of gas as the primary remaining source. (If ionization is still too large, we may need to add pumping or employ a more effective degassing of surfaces.) For electron emission coefficients of 100, 2-3 mA of electrons imply a loss of 20-30 $\mu$A of beam to each magnet in present experiments.

> **Yes** – go to 4. Determine conditions for obtaining minimal e-cloud and gas-cloud in a heavy-ion accelerator.
>
> **No** – go to 2. Replace HCX quad magnets with magnets that more smoothly continue the ESQ lattice parameters; or go to 3. Determine/improve the initial beam conditions.

**2. Issue**: **Halo formation continued – Replace HCX quad magnets with magnets that more smoothly continue the ESQ lattice parameters**. Theory and simulations suggest that the sudden transition from a ~45 cm ESQ lattice length to a 104 cm magnetic quad lattice length, separated by a drift region of ~18 cm (Diagnostics area D2) is likely to generate halo [24].

a. **Methods:** Install quadrupole magnets that smoothly continue the ESQ lattice. Proposed alternatives are
   I. Use existing NDCX quads of 1 m lattice length, following the first two matching ESQ quads that have similar length and diameter, which is also appropriate to the injector diameter.
   II. Build new quads of ~22 cm length and smaller diameter to smoothly continue the 10-ESQ array. Such magnetic quads have been designed, but not built or tested.
b. **Effectiveness:** Does this eliminate beam scraping in quad magnets? Can we reduce initial halo sufficiently to study sensitivity to match. Can we align scrapers sufficiently accurately relative to beam?
c. **Benchmarking:** Does this enable downstream simulations to better reproduce experiments, and reduce the need for an accurately reconstructed beam near the injector?

This concept eliminates the diagnostic region preceding the magnetic quadrupoles; we plan to mount the entire system on precision rails, as with NDCX, to enable the magnets to be pulled back to allow diagnoses of the beam going into the magnets, then replace the magnets which will be designed for rapid realignment.

These magnets (I) have a large inner bore, which allows large beam tubes that provide a larger gap between the beam and the beam tube, and/or allow space for diagnostics within quadrupole magnets. The large bore, plus halo scraping, should enable the beam to have minimal interaction with the beam tube, producing little or no electrons and gas. This then provides a baseline, with negligible electron and gas clouds, from which we can decrease the safety factors until electrons and gas become significant. It is essential, for future proposals, to be capable of providing baseline operation that we can guarantee to be free of degradation by electrons and gas; and to have the operational flexibility that we can also explore the limits where electrons and gas degrade operation.

**Decision point:** Can we reduce beam scrape off to a negligible level? Can we obtain predictive capability.

**Yes** –go to 4.
**No** – go to 3.

**3. Issue**: **Uncertainties in knowledge of initial condition of beam** (at source/injector) and the possibility that significant halo originates here. Ability of simulation to reproduce experiments is limited by uncertainties in precise locations of ion-emission surface and surrounding Pierce electrode, electron emission and gas desorption rates, and cross-sections for gas ionization, stripping, and charge exchange.

a. **Methods:** Investigate possible methods to provide a higher precision ion source that does not overfill the downstream beam transport. Provide diagnostics to obtain beam profiles and optical slit or pepper-pot data, sufficient to accurately reconstruct beam at source.
b. **Effectiveness:** Can injector be re-engineered to provide more accurate and reproducible alignment when hot. Can beam be injected within dynamic aperture of quads or solenoids (as with multi-aperture plasma source) to avoid immediate beam loss?
c. **Benchmarking:** Are these the main issues regarding the initial distribution? Need additional comparison of modeling to existing data? Use HCX (access difficult), or NDCX, or …? Do WARP reconstructions of beam enable accurate simulations further downstream?

Halo experiments on the Low Energy Demonstration Accelerator (LEDA) at Los Alamos discovered that the injected beam already had a diffuse halo at $10^{-3}$ to $10^{-4}$ of the peak beam, that extended to 9 rms radii, and reduced the sensitivity to small halo growth [22]. Similar effects could cloud our results.

**4. Issue: Reduce electron clouds to a negligible level** (E-clouds are caused by halo scrapeoff and ionization of gas particularly in long-pulse accelerators, and by multipactoring from a series of beam bunches in rf accelerators). We need to reduce these effects plus remove remaining electrons. Then we will be able to study limits on these and other parameters to maintain electron density below some low level)

a. **Methods:** Halo scraping, clearing electrodes, lower vacuum pressure, beam-tube coatings, alignment tolerances, lattice uniformity, matching accuracy & diagnostics to determine, fill factor allowed, …
b. **Effectiveness:** Can we achieve a significantly lower electron level?
c. **Benchmarking:** Compare experimental measurements with codes for each experimental variation that produces measurable effects.

At this point, we hope to have greatly reduced halo scraping as a source of electrons under some operating conditions. We may still have a significant ionization source: if so we need to reduce the vacuum pressure and gas desorption. Some possibilities here include

a. Add more pumping speed, possibly internal cryopanels or non—evaporable getters (NEG) pumps.
b. Move towards ultra-high vacuum (UHV) technology with hard seals rather than "O" rings. New magnets could incorporate this as they are added, and we could gradually move towards replacing the D-end diagnostics tank with a UHV version. However, we would still have the upstream portion of HCX using elastomer seals. Reduced diameter beam tubes in the magnets would be necessary to decrease the gas conductance for effective isolation the end diagnostics tank from the elastomer sealed upstream tanks.
c. Develop more effective outgassing techniques. The old standby of baking to high temperatures is not applicable to existing HCX

magnets, but might be possible with new UHV beam tubes if they could be thermally insulated from the surrounding magnets and perhaps some cooling provided for the magnet bores.

d. Try photon induced desorption, with cw fluorescent or pulsed flash tubes.
e. Try glow discharge cleaning. This was developed to a fine art for the SLAC PEP-II by LLNL. We could probably adapt those techniques. But, glow discharges are based on long-path Paschen breakdown, which is easier in a large vessel, than in small radius beam tubes.

Electron clouds are generally observed to provide a limit to the beam current [28]. However recent work predicts that even below the current limit, small electron cloud densities can cause slow emittance growth over thousands of turns in an accelerator ring, that could be disastrous for colliders where the number of interaction events decreases rapidly with increasing emittance and hence increasing beam size at the collision point [29]. These more subtle problems in accelerator rings may not be a problem in a linac.

Three questions need to be answered for both quadrupole and solenoid transport:

i. Is there a "beam threshold parameter" below which electron clouds are negligible, and what is the threshold?
ii. How fast do increasing e-clouds degrade the beam. We may need to separately answer this for each type of electron source: beam tube, end wall, and gas ionization.
iii. How large an electron cloud density can we tolerate from each type of source?

We currently have developed the tools to answer the second question in quadrupoles. We can measure the effects of electrons with slit scans, either conventional double slit [7] or optical slit scans with either solenoids and quadrupoles [30]; and we have developed techniques to measure the absolute value of the electron density in quadrupoles [31]. In solenoids, we need to develop and validate tools to measure the electron accumulation. We have only a short experiment in which to measure electron cloud effects, so it is essential to benchmark simulations with these results to validate the simulations that can then examine the effects in longer accelerators. We have shown that, with sufficient electron density, significant effects can be observed and accurately simulated with only four quadrupole magnets [32].

To answer the first question, we first need to obtain a negligible (i.e., below threshold) electron density, which is a goal of the experiments in Issues 1-3. Once that is accomplished, we can vary parameters to determine the critical parameters determining electron cloud density, and to determine the effect of electron clouds on these parameters.

We have performed initial experiments with solenoid transport, as a step towards answering the above questions, and comparing with quadrupoles to determine whether one is more effective at minimizing electrons or electron-cloud effects [33-35]. We have observed effects that appear to be caused by electrons. More work is required to understand and quantify these observations, and to achieve a predictive capability.

**5. Issue: Reduce gas-induced beam loss and degradation to negligible level.** (Very similar to (4) in importance to HIF, less important for WDM). Measurements have shown that energetic heavy ions striking walls at any angle, normal to grazing, desorb copious amounts of gas [3,25,26].

a. **Methods:** Halo scraping (possibly with hot apertures), simple-cold apertures, or pumped scrapers (analogous to pumped limiters in magnetic fusion devices [36]). Two initial experiments: (1) Measure and model the current to plates near the end wall operated as suppressors (ion current) or as dipoles with one plate positive (electron current). (2) Measure desorption Vs target temperature optically, T ranging from 77 K (liquid nitrogen temperature) to few hundred C for normal incidence. Such experiments would benefit from ultra-high vacuum. Consider using STS-500 pulser: can we achieve operation at 500 kV for 18-30 $\mu$s with a modified existing facility? Can we vary duration to check the scaling with time of gas-induced beam loss.

b. **Effectiveness:** If using hot apertures, what is the thermal load to possible nearby cold-bores in a future accelerator? What is the allowable gap between the beam tube and the beam versus the duration of the pulse (or pulse string), the time to the next pulse to allow for pumping, the gas velocity for desorption by grazing incidence ions (same as for normal incidence?)

c. **Benchmarking:** Compare WARP modeling with 1 MeV and 300 keV experiments (1), using gas, electron, and ionization modules.

**6. Issue: Longitudinal dynamics (beam-end & emittance budget)**

**a. Methods:** Careful design of the system is required — including spacing of ear pulses, acceleration schedule, and high-precision pulsers. Scrapers in #1 above may also remove slow rising/falling portions of head/tail as found with the DARHT BCUZ [23]. Head control is important to minimize electron and gas release by head, which can then degrade the remainder of the pulse; whereas tail control is mostly for the benefit of diagnostics, as the resulting gas and electrons will be lost before the next beam pulse.

**b. Effectiveness:** High-resolution energy analyzer measurements could determine the longitudinal temperature. Install a flexible induction cell on HCX or perhaps piggyback on the later NDCX experiments that will work with the beam head or tail; rearranging induction modules to allow the head to "bounce" once between ear applications would be very interesting.

a. **c. Benchmarking**: Can experimental results be predicted or reproduced with WARP?

**A major goal of studying issues 3 - 6** is to learn what is required to keep electron and gas generation small. We need to learn what is required to design an accelerator with assurance that it will provide a mode of operation with small halo, electron, and gas effects. In order to optimize performance of the next generation facilities, it should also include a broad-enough band of operation that it has modes with significant halo, electron, and gas generation. In this way, we accumulate the necessary knowledge in each generation of facilities to "bootstrap" our capabilities to the next generation facilities.

Other issues that can be addressed in the near term include:

**7. Issue: Negative ions eliminate e-cloud issues**, may be **lower emittance**, and are also easier to neutralize and focus in chamber, but are more easily stripped in an accelerator and especially in neutralized drift compression (if that used).

a. **Methods:** Operate ion sources with gases such as chlorine. Measure both negative and positive ion emission current density. Determine fraction of electrons as well as X+ and X- ion fractions. Measure emittance of both X+ and X-.
b. **Effectiveness:** Beam stripping increases as an issue, making ultra-high vacuum (UHV) more necessary, although Grisham estimates that ≤5% of the beam will be lost in a 1 km long beamline for pressures below $2.5 \times 10^{-8}$ torr, barely into the UHV range [37,38]. Cross sections for electron detachment reach 1-2 $\times 10^{-15}$ $cm^2$ for $F^-$, $Cl^-$, $Br^-$, and $I^-$ projectiles below 1 MeV incident on $N_2$ [39]. The scaling of this latter work to power plant energies is more favorable, allowing pressures to exceed that computed by Grisham by factors of 16 without, and 8 with multiple-electron losses in a single collision. Preliminary simulations of focusing beams through flibe vapor in a fusion chamber predict smaller spot size for photo-stripped (i.e., neutral) negative ions than for positive ions, probably because electrons that are stripped off the neutral beam can follow and continue to neutralize the beam charge [40].
c. **Benchmarking:** Do we have a code that can handle plasma sources? Experiments might use STS-100, or other source test stand with emittance diagnostics. These experiments could include diode-halo studies, and ion-ion plasma sheaths,

**8. Issue: Cause of Pulse Line Ion Accelerator (PLIA) breakdown**

**a.** **Methods:** Try to eliminate breakdown without beam first. If successful, add beams. If due to UV, could be relevant to ITER beams and existing JT-60U negative ion beams.
**b.** **Effectiveness:** If break-down fields increase to ~1 MV/m, and there is reason to believe that the ultimate limits are still higher, PLIA development will become a high priority.
**c.** **Benchmarking:** Use WARP and other codes to understand possible breakdown mechanisms, such as multipactor, or multiple impacts.

**9. Issue: electron and gas suppression in an unneutralized drift-compression beam line (final focus requires rapid neutralization w/o backflow into final optic)**

b. **Methods:** We could do a non-neutralized drift compression / focus experiment on a modified NDCX. Careful design of system (pumping, magnet design, clearing electrodes), and avoidance of halo in compression line via careful schedule would be necessary.

c. **Effectiveness:** Measure electron current or accumulation in drift compression and in accelerator. Can it be significantly reduced?
d. **Benchmarking:** Can experimental results be predicted or reproduced with LSP and WARP?

**10. Issue: time-dependent focal spot associated with energy variation**

a. **Methods:** Use time-dependent elements that appear promising in theory and simulations; or develop focusing systems inherently tolerant of energy variation ("achromats"). Perhaps near future tests on NDCX with electrostatic quadrupoles that are more easily swept rapidly than a magnet, and subsequent tests on a Linear Lithium Facility (LLF).
b. **Effectiveness:** Measure focal spot size and energy distribution near focus.
c. **Benchmarking**: Compare results with WARP and Mathematica-based models.

The following issues require facilities beyond minor upgrades of those existing.

**11. Issue: multiple-beam interactions in the driver** (non-constant deflections, "negative g factor" inductive effects and their implications for beam-to-beam differences & longitudinal instability). This is more of an issue for a magnetic quad array than for solenoids, and may be a factor in the choice, along with the feasibility of constructing precise multi-quad arrays. [Some of the issues, those regarding the perturbation of one beam by other beams, can be simulated by adding potential and current sources around a single beam. However, the possible interactions of a perturbed beam back on those causing the perturbation cannot be simulated by a single-beam experiment.]

a. **Methods:** Use careful design of system; dipoles for mean deflection; baffles for transverse shielding in gaps; module impedance constraints for longitudinal instability. Use bench tests to understand impedances of accelerating modules. We could also do near-term experiments with a single beam as an analogue simulation of electrostatic and magnetic effects of multi-beams on a single beam.
b. **Effectiveness:** What is the emittance and phase space of each multiple beam compared with a single beam?
c. **Benchmarking**: Compare experiments with enhanced WARP models.

**12. Issue: Multi-beam effects in chamber propagation;** must avoid failure-of-focus, asymmetric return currents, & deflections; and must focus the foot of a pulse before photoionized plasma is available.

a. **Methods:** We need high currents in each beam to produce HIF Driver-level magnetic and electrostatic forces on beams. To mitigate, we need enough plasma where the cluster of beam is dense; possibly from a sacrificial-defocused pre-pulse to make plasma near target?
b. **Effectiveness:** Planned NDCX experiments are relevant here, but we should try to interpret them in the light of the knowledge needed for an RPD-like system.

c. **Benchmarking:** Use LSP or enhanced WARP.

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## II. Critical issues for "novel" (neutralized drift, modular, and/or multi-pulsed) configurations

**13. Issue: e-cloud and gas in driver**; similar to above, but:

- multi-pulsing adds issues that should be investigated
- high q/m increases the beam's ability to attract electrons, and its susceptibility to stray fields
- backflow of plasma into the non-neutral part of the system upstream of the NDC line must be inhibited, as is already necessary in our experiments.

**14. Issue: longitudinal dynamics;** similar to above, but:

- shorter bunches will have different dynamics since they are "all ends"
- multi-pulsing at different energies may imply individually tailored "ears" for each pulse
- Again, high resolution energy analyzer measurements could determine longitudinal temperature, as well as head and tail energies.

**NEW OPPORTUNITY**

Beam halos are a concern in high-intensity high-brightness accelerators, including the Spallation Neutron Source (SNS), the Large Hadron Collider (LHC), and the Relativistic Heavy Ion Collider (RHIC), Warm-Dense Matter (WDM), Heavy-Ion Fusion (HIF), and other heavy-ion accelerators. Beam halos have previously proven to be difficult to study with experiments or simulations. In our e-cloud work, we have developed new and unique capabilities: experimental tools and validated simulation tools that evaluate the generation and transport of electrons and gas resulting from halo scraping, and that will enable us to work at a much more detailed and self-consistent level than could previous efforts. These new capabilities include

1. Reconstruction of the beam particle distribution that is used to initialize the simulation, based on the data from experimental x-y-x', and x-y-y' optical-slit scans (where the prime indicates the derivative with respect to the axial distance z). Results from Warp simulations with such "synthesized" input beams have been significantly closer to experimental results than those of simulations started with semi-Gaussian beams. We plan to take separate core and edge slit scans (the edge at higher gain) and "splice" them together (this will require some care with regard to thresholding and background noise, etc.). Initially, we will use the Warp's PIC model in a straightforward manner, but alternative methods, such as variable-weight particles or a Vlasov model, may be explored so as to achieve accuracy for the wide dynamic range without the need for a large number of simulation particles.
2. Measured desorption coefficients of gas, from ions striking walls: how it scales with the ion species, energy, and angle of incidence; and its subsequent transport and interaction with beams.

3. Measured and modeled electron emission coefficients from ions striking walls: its scaling, and the cross section for ionization of gas by beam impact.
4. Simulated the transport of electrons and their interactions with gas and beam.
5. Multiple developments that increase code operating speeds by several orders of magnitude, making it feasible to perform 3-D simulations with the added effects above. Speed enhancements include parallel operation, adaptive mesh refinement, particle timestep subcycling, and a drift-Lorentz electron mover tracking charged particles in magnetic fields using large time steps. For relativistic interactions of beams, a further few orders of magnitude reduction in computational time is possible, using our recent discovery of a preferred frame of reference.
6. Development of diagnostics to measure details that can be used for refining and validating simulations. These include gas and electron density within an ion beam, measurements of gas and electron emission from surfaces under beam bombardment, and optical slit scanners that provide information along the length of the slit in addition to the usual x-x', y- y', enabling cross terms to be evaluated and more realistic beams used in simulations.

Application of these developments has enabled us to quantitatively measure and simulate electron and gas cloud phenomena in detail, with experimental validation of many of the finer details of the simulations. Examples include: (1) Experiments show complex interactions of gas desorbed by beam impact, which can be ionized by subsequent beam ions. Collection of either ions or electrons reveals currents that increase in time. These are also observed in simulations, and are being used as tools to refine and validate the simulations. (2) Electron bunching within quadrupole magnets is observed in simulations and validated with arrays of capacitively coupled electrodes within a quadrupole magnet.

These new experimental and simulation tools are appropriate for studying halo scraping and regeneration, with confidence that our understanding can be significantly extended. We therefore plan to propose to extend our work on e-cloud, heavy-ion induced electron emission and gas desorption to experiments and simulations of halo scraping and regeneration. As input to the simulations, we will begin efforts to extend our reconstructions of beams to include halos

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